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Some Remarks on Soil Organic Matter Turn-Over in Swedish Podzol Profiles

The role of the soil organic matter in forest ecosystem dynamics has long been recognised. The organic matter forms an important part of the ion-absorbing colloids of the soil, in many cases the most important part. Moreover, it is of great importance to the structure and water-regime of the soil. The breakdown of the organic matter releases carbon dioxide and nitrogen in a form available to the plants. During the life of a forest, there is often an alternation between phases of accumulation and phases of dissipation in the humus layer. Accumulation is a normal process when a young stand is closing, and regular circulation of organic matter between stand and soil is re-established after a period during which not much litter is supplied to the ground. Accumulation may also occur where the breakdown processes are in check for some reason (poor aeration in wet soils, cold climate combined with unfavourable chemical composition of litter in some northern spruce forests). Dissipation, followed by the liberation of plant nutrients, nitrogen in particular, occurs after clear felling or forest fire. Even thinning affects the humus layer in the same direction, although to a lesser extent. ROMELL (cf. TAMM 1964) has called this phenomenon "the assart effect".

It is thus clear that the soil's organic matter and its variable biological properties are of the utmost importance to the forest ecosystem and to tree growth within the ecosystem. Many attempts have been made to characterise this organic matter, with respect to its morphological, physical, chemical and microbiological properties. Where the humus layer is concerned, macro- and micromorphology already supply important information (P. E. MÜLLER 1887, ROMELL 1935, JONGERIUS and SCHELLING 1960). Chemical and physico-chemical characteristics (acidity, rate of oxygen diffusion, chemistry of "humic acids" and related substances) have also been studied by many investigators (e.g. WITTICH 1952, HANDLEY 1954). It has often been assumed that more direct relationships are to be expected between forest growth and the microbiological processes in the soil, than between forest growth and other soil properties. Processes which have been studied in this connection are nitrogen mobilisation (HESSELMAN 1917, 1926, MORK 1938, ROMELL 1935, ZÖTTL 1964) and soil respiration (LUNDEGÅRDH 1924, ROMELL 1932, MORK 1938, WALTER & HABER 1957). Many important results have been obtained, but no-one has so far found simple traits generally applicable to the problem of the variation in soil fertility. One reason for this is the difficulty of applying the results of laboratory tests to

conditions in nature, a problem discussed particularly by ROMELL 1935 (cf. also MORK 1938 and TAMM 1964).

This paper reports some data connected with the problem of the turn-over of organic matter in northern coniferous soils. The earlier work discussed above gives us a fairly good idea of what happens in the mor layer of a forest during a rotation, although the lack of satisfactory quantitative information makes it difficult to relate forest growth to specific soil processes. A large part of the organic matter in the mor layer is apparently very closely related to the living vegetation, being formed by partly decomposed but still recognisable plant remains. This material is also a main source of nutrients for the trees, as witnessed by the high frequency of rootlets and mycorrhizal hyphae. There is reason to believe that often 90 per cent or more of the trees' uptake of nitrogen comes from the mor layer. A deterioration in this layer is therefore a very serious matter to the ecosystem, particularly on sites from which nitrogen-fixing organisms (e.g. nodule bacteria) are absent, and where the atmospheric supply of bound nitrogen is low.

On most podzol sites, however, the mor layer contains a minor part only of the soil's organic matter. The accumulation or B horizon usually contains more organic matter than the A_0 layer; smaller quantities are also found in the A_1 and A_2 horizons. Some organic matter is also present in the subsoil, but the quantity is usually only just detectable by ordinary analytical methods. There is always some nitrogen in the humus of the mineral soil horizons; the nitrogen percentage of the B horizon's organic matter usually exceeds that of the mor. There is also reason to believe that considerable parts of the soil's phosphorus and sulphur, and other plant nutrients, too, are linked up with the organic colloids. Evidently, the large stores of organic matter and nutrients in the profile below the A horizon are valuable assets to the ecosystem in the long run, always supposing that the plant nutrients there are not permanently unavailable. Circumstantial evidence for their importance may be found in that the frequency of roots is higher in the B horizon than it is just above and below this horizon. It is also worth noting that many sites (but not all) seem to have a remarkable ability to regenerate a new humus layer after stand, vegetation, and much of the mor layer have been destroyed by a forest fire and the subsequent dissipation phase. An annual atmospheric supply of one or a few kilograms per hectare of bound nitrogen can hardly explain the accumulation of 500 kg/ha, a value often found in a 100-year-old stand.

The simplest way of studying the availability of the plant nutrients bound in the B horizon would be by some kind of incubation experiment, in which soil samples were stored under more or less controlled conditions, and the

released nutrients extracted chemically or by roots in pot experiments. Many such experiments have been carried out, and have invariably shown that the B horizon releases much smaller amounts of nutrients than a mor layer. Short-term experiments usually give no measurable production of ammonia or nitrate. Some experiments extending over two years or more have been carried out in this laboratory (TAMM & PETTERSON, in prep.), and amounts varying from nil to about five per cent of the total nitrogen in the sample were then transformed into ammonia and nitrate. Results of this type, however, do not tell us whether the nitrogen released occurred originally in a form similar to that of the 95 per cent not released. Neither do they tell whether some of the released nitrogen was fixed again, as it may well be in samples with a high C/N ratio. Experiments with labelled nitrogen might solve the latter, but not the former, problem.

In looking for other ways of judging the rate of decomposition of the soil organic matter, we have tried to obtain information about the approximate residence time of the organic carbon on the site by means of a determination of the C^{14} content (cf. SIMONSON 1959). This paper reports a series of radiocarbon datings of soil organic matter, earlier published in very brief form only (TAMM & ÖSTLUND 1960, ØSTLUND & ENGSTRAND 1963.) Unfortunately, we had no technical means of fractionating the organic matter before the C^{14} measurements, as is desirable (cf. PERRIN et al. 1964, and VASARI 1965). However, the results as they are seem to shed some light on what is going on in the soil inboth North and Middle Sweden.

Description of sample plots

Group I, Samples from Middle Sweden

(Described by C. O. TAMM)

The samples first dated were collected from three very different sites in Middle Sweden. Two of the profiles were sampled by one of us (COT), while the remaining two samples were taken in 1934 by O. Tamm. Some data about these samples were published by O. TAMM (1937, Fig. 5 and 6), but the exact location of the sampled pit is not known. All three sites have also been sampled for other purposes, and some of the data in Tables 1 and 2 therefore concern other profiles from the same sites, similar to, but not absolutely identical with, the profiles sampled for radiocarbon dating.

As nothing was known beforehand of the C^{14} content of the soil organic matter, three samples were investigated from various horizons of the first profile (GARPENBERG), a vigorous moss-rich spruce forest in the southernmost part of the North-Scandinavian conifer belt. The same samples were also

Table 1. Middle Swedish plots. Some site and soil characteristics.

Site	Lat. N.	Long. E.	Altitude m	Podzol type	Soil characteristics: Depth of soil horizons, cm A_0	A_1	A_2	B	$d\ 75\%$ µ *	Base mineral index (C)	Further characteristics	Moisture regime and parent material
Garpenberg	60° 16′	16° 13′	196	iron	7	4	0**	16	10 (C)	8	Humus layer mor, seldom mull-like	Well-drained glacial till
Havtjärn-heden	61° 21′	13° 29′	500	iron–humus	3	0—1	11	10	100 (B)	2	Humus layer mor, hardpan Very stony	Well-drained glacial till
Haboskogen	57° 59′	14° 00′	240	iron–humus	6	0—1	14	25	100 (C)	0.9	Humus layer mor, hardpan	Excessively drained outwash sand

* diameter of the soil particle at the lower quartile of the size distribution curve (75 per cent of the material is coarser, 25 per cent finer). ** 1—3 cm A_2 occurring in patches.

Table 2. Middle Swedish plots. Tree stand and amounts of organic matter and nitrogen in soil.

Site	Proportion of tree species: pine	spruce	hardwood	Age	Current growth m^3 per ha	Loss on ignition, in 1,000 kg per ha: A_0	$A_1 + A_2$	B	Amount of N kg per ha: A_0	$A_1 + A_2$	B
Garpenberg	0.3	0.7	—	95	5	67	34	106	1150	650	2330
Havtjärnheden	1.0	—	—	130	≤ 1.5	24	17	28	290	270	420
Haboskogen*	1.0	—	—	70	3	52	25	37	740	530	520

* Sample plot 876 : I. Dated profile with some more spruce undergrowth.

Table 3. Middle Swedish plots. Carbon content and formal age of dated samples.

Site and date of sampling	Sampled horizon	Loss on ignition %	C %	C/N	Formal age, years
Garpenberg 21.11.1958	A_0	45.5	24.0	26	low (98.3 ± 0.5 % C^{14})
	A_1	15.9	7.3	21	low (98.0 ± 0.5 % C^{14})
	B	5.2	2.1	19	370 ± 100* (95.6 ± 0.5 % C^{14})
Havtjärnheden 20.10.1959	A_1 (with some A_0)	18.4	9.4	42	140 ± 80
	A_2	3.9	2.6	49	230 ± 85
	B_1 (with some B_2)	10.8	3.9	26	400 ± 80
Haboskogen 5.9.1934	B_1	3.2	1.4	27	330 ± 65
	B_2	2.1	0.8	26	465 ± 65

* See text p. 000.

studied with respect to their capacity for mineralising nitrogen (TAMM & PETTERSON, in prep.). Further information on this site may be found in TROEDSSON & TAMM, in prep. From the next profile, too, an extremely poor "lichen-pine" forest at higher altitude in Middle Sweden (cf. MALMSTRÖM 1963), three samples were submitted to dating, but the main part of the A_0 horizon was left out, as it could be assumed to have a low age. The horizons sampled comprised the transitional zone between A_0 and A_1, the unusually deep A_2 horizon, and the upper part of the B horizon (mainly the dark-brown B_1, but also including patches of more rust-coloured B_2). From the third site, Haboskogen, two samples were dated, the dark-brown B_1 and the rust-coloured B_2. This site must also be characterised as poor, owing to the coarse texture of the soil and the lack of mineral nutrients in the quartz-rich sand (O. TAMM 1937).

All three sites are situated above the highest post-glacial shoreline (Garpenberg only just above), and in flat terrain. The geology of the Garpenberg area is fairly normal for Swedish conditions (granites and leptites dominating in the bedrock, with local occurrences of less acid rocks). Havtjärnheden, however, lies within an area with extremely poor bedrock (quartzitic sandstone and weathering-resistant porphyry). Its being near the former ice divide precludes the till, which is also unusually coarse, from any greater admixture with material transported for long distances. Haboskogen is situated on an extensive plain of glacifluvial sand, formed in an ice-dammed lake during the retreat of the ice. Climatically, Havtjärnheden represents a cold and humid site (annual mean temperature + 1.5° C calculated according to ÅNGSTRÖM 1938, and annual precipitation about 650 to 700 mm, judging from data for the stations Särna and Evertsberg). Haboskogen has a warmer climate (calculated annual mean temperature + 5.7° C; annual precipitation about 600 mm). Garpenberg is intermediate as regards temperature (+ 4.1° C; precipitation about 600 mm).

Group II, Samples from Lappland
(Described by H. HOLMEN)

In the middle of the 19th century there began an exhaustive exploitation of the forests in the interior of northern Sweden. During the next fifty years, extensive areas of forest were almost completely despoiled of their larger trees. In many places the stands remaining were very sparse, and had small or large gaps. Not until the 1940s and 1950s were large-scale efforts made to restore the devastated forests. Thus, commonly, all large trees were felled during the later 19th, and the earlier part of the 20th century. Further fellings for both timber and pulpwood took place after World War I and during the third decade of the 20th century, the final clear-cutting being carried out after World War II.

The difficulties of regenerating the forests in many of these ill-managed areas have been sought in changes in microclimate, in attacks of fungal parasites, and also in changes in soils which have been treeless or poorly stocked for a long time. Thus "heath-degeneration" and "inactivation of the humus layer" are terms used to describe the condition. Problems connected with this have been studied in some detail at the College of Forestry in recent years. Certain problems were of particular interest; first, the investigation of the nutrient supply in the "residual stands" as compared with that in the well-managed stands, and secondly, the study of the content of organic matter and its turnover in the soil. It was of great interest, too, to find whether the supposed changes in the humus layer were followed by corresponding changes in the B horizon's humus. Radiocarbon dating was one possible way of measuring such changes.

To this end, samples were collected from eight pairs of plots. The one plot of each pair (reference plot, R plot) had a stand development considered "normal" for the area. These plots were chosen from the permanent or temporary plots of the Forest Research Insitute. The other plot of each pair (comparison plot, J plot) was chosen from the neighbourhood, and in all primary factors (topography, soil texture, hydrology, etc.) resembled as closely as possible its partner; but the forest was in poor condition, and was a residual stand if one still existed.

The sample plots were situated between 65° 35′ and 67° 41′ N.lat., i.e. on the Arctic circle. The altitude varied from 200—550 m above sea level, which is well above the highest post-glacial shoreline in the area. The bedrock consisted mainly of acid rocks such as granites, gneisses and leptites, but there were small areas with less acid rocks such as diabase. The mean annual temperature was — 2° to 0° C, and the annual precipitation 450—550 mm.

About 60 per cent of the land area below the forest limit is forested in northern Swedish Lappland. The annual increment of the forest is very low, as is the average volume of the stands, 1.2 m^3 and 50 m^3 per ha respectively. These figures, which refer to northern Lappland, are the lowest in the country for a productive forest area (ARMAN 1965). Pine, and mixed coniferous and deciduous stands, occupy about 75 per cent of the forested area.

Vegetation of the sample plots

The tree stands of the sample plots consisted mainly of pine, except on plot 967 J, where spruce was the dominant species, 85 per cent by volume. Hardwoods also occur *(Betula pubescens, B. verrucosa,* and sometimes *Populus tremula)*. The total volume of the R plot stands varied from 130—245 m^3/ha, and the total yield during the rotation has been estimated at 145—270 m^3/ha.

Table 4. North Swedish plots. Some site and soil characteristics.

Plot No	Lat. N	Long. E	Altitude m	Podzol type	Depth of soil horizons, cm			$d_{75\%}$ μ (cf. Table 1)	Base mineral index B horizon	Stoniness*	Further characteristics
					A_0	A_{1+2}	B + B/C				
610 R	66° 38′	19° 42′	280	iron	5.9	7.0	33	37	8	24	
610 J	66° 35′	19° 42′	330	iron	6.4	5.0	38	44	19	23	
967 R	65° 35′	18° 24′	535	humus	4.6	9.0	41	32	9	19	
967 J	65° 35′	18° 24′	520	iron–humus	3.0	8.4	33	175	12	19	coherent hardpan
972 R	65° 38′	19° 54′	435	iron	3.4	5.6	39	42	16	17	
972 J	65° 35′	19° 54′	435	iron	1.2	5.2	43	30	13	17	mottling in C horizon
991 R	66° 37′	18° 54′	410	iron	6.8	8.1	41	140	11	28	
991 J	66° 37′	18° 54′	410	iron	3.5	6.1	34	130	11	24	
992 R	66° 38′	19° 00′	400	iron	4.2	5.7	32	38	17	24	
992 J	66° 38′	19° 00′	400	iron	2.8	5.1	24	48	14	23	
1404 R	67° 02′	20° 24′	450	iron	3.8	9.8	51	70	20	18	mottling in C horizon
1404 J	67° 04′	20° 24′	455	iron–humus	3.9	9.1	49	52	16	16	coherent hardpan
1405 R	67° 41′	21° 18′	320	iron	5.8	4.9	50	29	38	23	
1405 J	67° 39′	21° 18′	325	iron	4.0	5.1	45	53	14	20	mottling in C horizon
1416 R	67° 13′	22° 12′	190	iron	2.6	4.4	56	27	21	26	
1416 J	67° 15′	22° 12′	210	iron	3.3	4.5	72	42	21	23	

* Determined as depth index according to Viro (1952).

Table 5. North Swedish plots. Tree stand characteristics.

Plot No	Proportion of tree species			Age[1]) years (pine)	Site class[2]) h_{100} m (pine)	Estimated yield[3]) m^3/ha/year all species	
	pine	spruce	hardwood				
610 R	1.0	—	—	107	16.0	2.6	[1]) Ages not strictly comparable because of the different methods used in their determination. Figures within brackets mean that the stand had been felled and ages were determined from stumps
610 J	0.6	0.3	0.1	225	—	1.6	
967 R	0.8	0.2	—	92	16.0	1.6	
967 J	0.2	0.8	—	80	14.5	0.6	
972 R	1.0	—	—	98	17.3	1.6	
972 J	1.0	—	—	(95)	—	1.2	
991 R	0.8	0.1	0.1	97	14.8	1.6	[2]) Site class is defined by the dominant height at a stand age of 100 years at breast height
991 J	0.9	—	0.1	160	13.8	1.0	
992 R	0.9	—	0.1	91	15.8	2.2	
992 J	0.6	0.1	0.3	190	—	0.8	
1404 R	0.9	—	0.1	93	16.3	2.2	[3]) Figures for the treeless J plots determined by diameter and annual ring measured ages on stumps
1404 J	0.6	0.2	0.2	200	—	0.6	
1405 R	0.9	—	0.1	95	17.0	2.0	
1405 J	1.0	—	—	(250)	—	1.4	
1416 R	1.0	—	—	84	17.0	2.1	
1416 J	1.0	—	—	(210)	—	2.1	

Fig. 1. Example of a camparison plot (1416 J). The first identified cutting was carried out in the period 1900–1910, and the clear-felling in 1950. See further tables 4—6. Photo september 1960.

The average age of the stands was about 100 years, and the annual yield was 2.0 m^3/ha.

The J plots had heavily-thinned stands, or lacked trees. With the help of stumps, forest maps, and verbal information it was possible to discover something of the history of these stands at various times. The maximum age of the stands (including the clear-felled stands-, was 100—250 years, and the mean annual increment during the past 50 years has been estimated at about 1.2 m^3/ha, i.e. slightly more than half that of the reference plots.

The prevailing vegetation of the field layer consisted of dwarf shrubs, mainly *Vaccinium* species. On the well-stocked plots, *V. myrtillus* was quantitatively the most important species; on the open or poorly stocked plots, *V. vitis-idaea*, *Empetrum hermaphroditum* and *Calluna vulgaris* were most common. On most plots were also found *Ledum palustre*, *Linnaea borealis*, *Lycopodium* species and *Deschampsia flexuosa*. Herbs were few both in number of species and in number of individuals; the most common was *Chamaenerion augustifolium*.

The dominant moss of the bottom layer was *Pleurozium schreberi*. *Hylocomium splendens*, common elsewhere, had only a low degree of cover and fre-

Fig. 2. Example of a reference plot (1416 R). See further tables 4—6. Photo september 1960.

quency. *Dicranum* species, especially *D. fuscescens*, and *Polytrichum juniperinum* occurred constantly. Of the lichens, *Cladonia* species were dominant on some plots, but other lichens, e.g. of the genera *Stereocaulon*, *Cetraria*, *Peltigera* and *Nephroma*, were present, too.

Description of soil profiles

All sample plots lay on sandy to finely sandy glacial till, but there were also local occurrences of soils which seemed to have been assorted and redeposited in water (plots 610 R, 991 R and J). The soils were most often iron podzols (see table 4). Some modification of the typical iron podzol could be seen. Thus there was, for instance, a more or less distinct mottling on the walls, in the deeper parts (60—115 cm) of the soil pits on plots 972 J, 1404 R and 1405 J, indicative of a periodically high, stagnant water table. The water table in the sample pits varied at the time of sampling between five and 50 cm in plot 967 R, and between 40 and 80 cm below the soil surface, in plot 967 J. In the other plots no free water was seen even at a depth of 100—140 cm. Hardpan occurred in six plots, mainly as small concretions. In two cases it appeared to be coherent (967 J and 1404 J), and here the soil was an iron-humus podzol (table 00).

Laboratory determinations

The C^{14} determinations were made at the Radioactive Dating Laboratory, Geological Survey of Sweden, Stockholm, by their standard procedure. All the data were corrected to the same initial isotopic composition by measuring the ratio of C^{13} : C^{14} in the samples (ÖSTLUND 1957).

A change in standard for the C^{14} measurement between the Garpenberg samples and the rest of the material has caused there to be a small difference in apparent formal age, although this difference is well within the standard error of the determination. According to ÖSTLUND and ENGSTRAND (1961), 55 years should be subtracted from the older values to make them fully comparable with the younger ones.

The other analytical data in Tables 1—6 are results from standard laboratory methods. Loss on ignition was determined by igniting the samples to constant weight in a muffle furnace at 550° C, organic carbon by digestion ("wet combustion"- according to VESTERVALL (1963), or in some cases, to JANSSON & VALDMAA (1961). On the average, organic carbon amounted to about 30 per cent of the loss on ignition (range 18—40 per cent) for the horizons $A_{1,2}$ and B. Nitrogen was determined by the Kjeldahl method.

Results and discussion

Except for the dating lists from the Stockholm Radioactive Dating Laboratory, only preliminary notes of the present investigations have been published so far (TAMM and ÖSTLUND, 1960, for the Garpenberg profile, data for Havtjärnheden in MALMSTRÖM, 1963, and data for the Lappland plots by HOLMEN, 1961). Other studies were made on the samples of group I (incubation experiments on nitrogen mobilisation, TAMM and PETTERSON, in prep.). The sample data from group II represent only a part of the information available for judging the effect of stand mismanagement on soil, and a further publication is planned. The present discussion must therefore be considered preliminary where the nitrogen cycle and the possible differences between R and J plots are concerned.

The data in Table 3 confirm the opinion that the A horizon's humus is, to a large extent, the product of the last forest generation. The humus in all three profiles appeared to become older with increasing depth. In every case there seemed to be smaller amounts of organic matter and nitrogen in the A_0 horizon than in the mineral soil, even though the B horizons on the poor sites Havtjärnheden and Haboskogen had a low humus content, despite their dark-brown colour. Both sites also had a high C/N ratio in all horizons.

Table 6. North Swedish plots. Organic matter (loss on ignition) and amount of nitrogen of various soil horizons and formal age of the accumulation horizon's organic matter.

Plot No	Loss on ignition, per cent of dry matter			C content B horizon	Loss on ignition, in 1,000 kg per ha			Amount of nitrogen kg per ha			C/N		Formal age, years B horizon
	A_0	$A_{1,2}$	B		A_0	$A_{1,2}$	B	A_0	$A_{1,2}$	B	A_0	B	
610 R	81.9	1.6	4.2	1.1	50	14	130	590	270	1550	40	20	500 ± 65
610 J	79.7	1.5	3.5	1.0	55	10	120	500	200	1400	50	25	460 ± 65
967 R	74.9	1.3	6.8	2.1	65	15	260	780	350	3800	35	20	620 ± 65
967 J	73.0	1.7	7.0	2.5	30	18	210	360	330	3700	35	20	1260 ± 60
972 R	67.7	1.9	6.2	1.7	45	14	220	370	220	2900	45	20	590 ± 75
972 J	40.1	1.9	4.4	0.8	20	13	180	220	270	2800	20	10	670 ± 65
991 R	79.8	1.2	2.1	0.6	55	13	80	750	320	380	35	60	750 ± 60
991 J	62.6	1.3	2.0	0.8	15	11	65	190	160	650	25	40	910 ± 65
992 R	79.8	2.8	4.6	1.5	55	21	200	750	300	2250	35	30	630 ± 65
992 J	64.6	2.3	3.6	1.2	25	15	120	370	330	2000	25	20	490 ± 60
1404 R	67.9	1.3	2.9	0.9	35	17	140	420	250	1450	35	30	730 ± 80
1404 J	57.8	1.3	4.4	1.4	30	14	200	480	330	4600	20	15	760 ± 65
1405 R	69.7	2.4	3.3	1.0	45	15	150	480	190	1900	35	25	480 ± 90
1405 J	62.5	1.7	3.2	1.0	35	12	130	400	200	2100	20	20	705 ± 65
1416 R	62.8	1.9	3.0	0.8	40	11	150	350	110	1550	40	25	470 ± 80
1416 J	57.7	1.8	2.7	0.7	40	11	180	510	180	2700	25	20	780 ± 60

In the Lappland plots, only the B horizon's humus was dated (Table 6). The formal ages obtained were, on the average, higher than those in group I, but the difference was not statistically significant. However, within the R plots of group II there is also a slight tendency to higher formal ages with increasing altitude (= colder climate). The average for J plots was somewhat higher than that for R plots (750 as against 600 years), and the differences in formal age could not be attributed to the altitude. If the very high figure for plot 967 J (1260 years) was excluded, the average for the J plots was decreased to 680 years. The difference in age between the R and J plots was about ten per cent, and thus agreed with what might have been expected, had the supply of fresh organic matter to the B horizon in the J plots been reduced some 50 to 100 years ago. As was stated above, the difference was not statistically significant, because of the wide scatter of the data.

Tables 4 and 5 show that in the Lappland plots, 70—80 per cent of the sites' store of organic matter and nitrogen were in the B horizon, only about ten to 20 per cent being in the A_0, and five to ten per cent in the $A_{1,2}$. The A_0 of the J plots contained considerably less both of nitrogen and of organic matter than the A_0 of the R plots, often only half the amount. This agreed with the general assumption, but it is satisfying to note that—at least in the present eight pairs of samples plots—the signs of site deterioration seemed to be absent from the $A_{1,2}$ and B horizons (apart from the small difference in formal age).

Turn-over of organic matter and site productivity

The data presented give us, as discussed above, only a limited opportunity of drawing conclusions about particular profiles or pairs of profiles. However, they can be used as the starting point for a somewhat speculative discussion along at least two different lines, one of which was touched upon in the introduction, viz.: What part does the B horizon's humus play in site productivity? As northern coniferous forests often suffer from a pronounced nitrogen deficiency, the large stores of nitrogen in the B horison are of particular interest, although it is clear that most of the tree's uptake is from the A_0 horizon in a normal forest stand (cf. p. 000). In arable soils, it has been estimated that annually about one to two per cent of the total nitrogen store is broken down to ammonia and nitrate (Nömmik 1963). As soil working promotes this decomposition, a virgin soil could, for this reason, be expected to release less nitrogen (cf. also Romell, 1935). Then follows the question of low temperature (particularly in Lappland and at Havtjärnheden), the high acidity, and in some profiles at least, periods with poor aeration, all of these being factors with a retarding influence on some or all of the processes involved in the breakdown

of organic matter. However, a rate of release of one tenth of the quantity just mentioned, or 0.1—0.2 per cent annually, would mean that in a site with a store of 2,000 kg nitrogen per hectare in the B horizon, two to four kilograms would be made available to plant roots. The formal ages listed in Tables 3 and 5 suggest that the release of carbon is of the order 0.1 to 0.2 per cent of the total amount in the B horizon. But it cannot be taken for granted that the release of nitrogen is equivalent to the release of carbon. Long incubation of samples of the B horizon from Havtjärnheden yielded no measurable quantities of ammonia or nitrate, while small amounts were obtained from the Garpenberg and Haboskogen samples (TAMM and PETTERSON, in prep.). Presumably much of the nitrogen released is fixed again biologically or chemically in a soil with such a high C/N ratio as that at Havtjärnheden. Yet tree roots and mycorrhizal hyphae may be able to compete with other organisms for nitrogen compounds which temporarily become available. Thus it is of interest to compare the hypothethical quantity of nitrogen released annually, two to four kilograms, with the only established external source of nitrogen in this type of forest ecosystem: the bound nitrogen contained in precipitation. This supply is probably less than one kilogram per hectare in Lappland (ERIKSSON 1966), and as the run-off water contains some nitrogen, the net gain will be less. Unless there exists some unknown type of biological fixation of atmospheric nitrogen in poor acid coniferous forests (lichens and blue green algae have been discussed), this type of ecosystem must build up the nitrogen necessary for maintaining an internal circulation, from very limited annual gains (from precipitation and perhaps from the uptake of gaseous ammonia).

The deposition of large amounts of nitrogen in the B horizon of a podzol profile, in a form in which it is very slowly released, may at first be considered a waste of nature's resources. In the long run, however, this store may give a stability of great importance to the ecosystem, as, for instance, after a forest fire. It is not impossible that the changes in soil temperature and vegetation after clear felling or a fire temporarily increase the breakdown in the B horizon, too.

Very little is known about the fate of nitrogen released in the B horizon. Some will be taken up by organisms, some will be bound chemically, and some will be leached out. It is even possible that some of the fertilizer nitrogen not used by vegetation will be bound chemically in soil organic matter, which could explain the low leaching losses reported by COLE and GESSEL (1965).

Breakdown of organic matter and the process of podzolisation

The breakdown of organic matter is also of considerable pedological interest. The generally accepted picture of the podzolisation process seems to be as follows: Decomposition process in the acid mor produce water-soluble organic substances with chelating properties, which act as carriers of iron and aluminium ions, released from the minerals in the A_1 and A_2 horizon under the influence of hydrogen ions. Capillary movement transports the chelates downwards, until they meet a less acid environment where they (or at least iron and aluminium hydroxide) precipitate, presumably at their isoelectric point (MATTSON and LÖNNERMAK 1939). Model experiments have been carried out, showing that the mechanism is possible under laboratory conditions. The rate of the process in the field is known only in a very broad sense (O. TAMM 1920, JENNY 1940, FRANZMEIER, WHITESIDE and MORTLAND 1963).

The process described is in good agreement with the usual pH trend in the soil, where the B horizon is less acid than the horizons A_0, A_1, and A_2. Neither is there any reason to doubt the occurrence, during part of the year at least, of a downward capillary water movement from the A to the B horizon, although evidence has been produced to show that some of the downward water movement in forest soils follows root-channels and other pre-formed watercourses (TROEDSSON 1955). What appears more questionable to the present authors is the mechanism for maintenance of a given pH in the B horizon. The source of the metal ions responsible for the higher base-saturation in the B than in the A horizon must be the weathering of minerals in the B horizon, unless we make a further assumption about a regular alternation between upward and downward water movement, an assumption which seems difficult to apply to the rather different climates under which we find podzols.

There have been attempts to calculate the rate of weathering in podzols, both from the mineral composition of the horizons (O. TAMM 1950) and from chemical analysis of the drainage water (cf. VIRO 1953), but the latter type of measurement usually results in too high figures, because the atmospheric supply is underestimated. The former method gives very low values for the annual release of metal ions, except in cases where easily weathered mineral species are present in the soil profile.

If the release of cations from minerals in the B horizon is too low to account for the permanent trend in acidity and base-saturation from the A to the B horizon, we must resort to the alternative explanation, viz. that soluble acids or acid groups in the gel complex are destroyed in the B horizon. Many authors have suggested that microbiological decomposition of organic carriers might play a role in the precipitation of iron and aluminium in the podzol B horizon, even if most of the evidence produced in favour of this opinion is indirect only

(GALLAGHER 1942, STOBBE and WRIGHT 1959, CRAWFORD 1963). It is easy to demonstrate that organic acids of low molecular weight, such as oxalic, malic, and citric acid, are rapidly decomposed in aerobic extracts or soil columns. NYKVIST (1963, and in press) has made some very instructive experiments with litter extracts, in which the breakdown of, i.a. malic and citric acids decreased acidity by several pH units. He does not believe that these particular acids play any part in the process of podzolisation, because they are so rapidly decomposed, but he apparently considers that a similar mechanism is possibe in the case of more stable acidic substances, too.

The performance of conclusive model experiments on microbiological decomposition meets with considerable difficulties, both because the process is rather slow, and, in particular, because we do not know the chemical nature of the substances in question. We must therefore be content with somewhat circumstantial evidence, and this is where the results of the present investigation come in, showing that the organic matter once deposited in the B horizon really is subject to breakdown (cf. also C. O. TAMM, 1957). As soil organic matter in podzol profiles is predominantly acid in character, such decay also means a decrease in acidity.

All the sites in Tables 1 and 4, with the possible exception of Garpenberg, have probably been covered with conifer forest, mostly pine, during the main part of the postglacial era, 8,000—10,000 years. Forest fire may have caused shorter periods with dominating hardwoods, but climate and soil would still have directed the soil processes towards podzolisation. A formal age of at least some thousand years would be the result of a steady accumulation of organic matter without breakdown's having occurred. Our samples, all except one, are younger than 1,000 years in formal age.

More detailed comparisons, both between the various sites and between our sample plots and other ecosystems, can probably be made by the method used by ODÉN (1961), but since some of the items in the balance sheet are not sufficiently well known, more accurate comparison is not possible.

A further observation worth noting is that the oldest sample, 1260 $\pm$ 60 years, originated from an iron-humus podzol. In northern Sweden, this podzol type indicates a somewhat poor drainage, and it is possible that this poor drainage has retarded the organic matter's decomposition. The other iron-humus podzol in this series, as well as the profile described as a humus podzol, shows, however, an age similar to that of the majority of profiles. Both iron-humus podzols in group I (Table 3) are well-drained. Like VASARI (1965), we should like to draw attention to the relatively low age of North-Scandinavian podzols, even iron-humus and humus podzols, as compared with that of some British and German examples (PERRIN et al. 1964, LÜDERS 1961).

Summary

Soil organic matter from various horizons of three podzol profiles in the southern half of Sweden, and from the B horison of eight pairs of profiles from northernmost Sweden, were dated by means of the C^{14} method. The three first profiles represented widely different forest types, while the remaining profiles were taken from relatively uniform moss and lichen rich forests. One plot in each pair had a satisfactory forest stand, while the other plot represented a residual stand (or a clearing) after repeated selective cutting.

Only the B horizon's humus could be dated with any certainty, even though the figures obtained for A_1 and A_2 humus from the poorest site (Havtjärnheden) suggest that part of this humus may be older than the present forest generation. The formal ages obtained varied from 330 $\pm$ 65 to 465 $\pm$ 65 years for B humus in the southern group, and from 460 $\pm$ 65 to 1260 $\pm$ 60 years in the northern group. Within the latter group, no consistent difference was obtained between good forest plots and devastated sites.

It is considered proved that a continuous break-down of humus is going on in the B horizon of podzol profiles, and the large stores of organic matter and nitrogen in this horizon make this process interesting from the point of view of productivity. As the process of podzolisation involves movement, precipitation and decomposition of organic matter, some pedological implications are also discussed.

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